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Michael J. Verrilli and Lisa C. Martin
Glenn Research Center, Cleveland, Ohio

David N. Brewer
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

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National Aeronautics and
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Michael J. Verrilli and Lisa C. Martin
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

David N. Brewer
U.S. Army Research Laboratory
Glenn Research Center
Cleveland, Ohio 44135

ABSTRACT

Combustor liners, manufactured from silicon carbide fiber-reinforced silicon carbide, (SiC/SiC), were tested for 260 hrs using a simulated gas turbine engine cycle. This report documents the results of the last 56 hours of testing. Damage occurred in one of the six different components that make up the combustor liner set, the rich zone liner. Cracks in the rich zone liner initiated at the leading edge due to stresses resulting from the component attachment configuration. Thin film thermocouples and fiber optic pyrometers were used to measure the rich zone liner's temperature and these results are reported.

1.0 INTRODUCTION

A ceramic matrix composite, silicon carbide fiber-reinforced silicon carbide, (SiC/SiC) is being evaluated for use as a combustor liner material for aircraft gas turbine (refs. 1–2) and power generation turbine engines (refs. 3–8). The use of SiC/SiC composites as combustor liners can lead to more efficient engine operation and lower NO_x emissions because of the higher use temperature of SiC/SiC compared to the state of the art superalloys currently in use. Data on the durability of SiC/SiC composites in the combustor environment is required to verify operational assumptions and validate design practices.

To test SiC/SiC components in a combustion environment, the Rich-burn, Quick-quench, Lean-burn (RQL) sector rig was developed at NASA Glenn Research Center under the High Speed Research/Enabling Propulsion Materials (HSR/EPM) program. The purpose of the sector rig testing was to demonstrate the structural durability of the SiC/SiC liners in a combustion environment where stresses, temperatures, and pressures would as accurately as possible reflect the operating conditions found in a turbine engine. A HSR program goal of 200 hours of rig operation at aircraft combustor conditions was achieved (refs. 1–2).

In the present study, 56 hours of additional testing of SiC/SiC combustor liners were conducted in the RQL sector rig. This effort focused on the evaluation of improvements to the sector rig in order to eliminate the damage in the rich zone liners observed during previous testing (ref. 1). It also served as a means to evaluate advanced techniques for measurement of the temperature of the SiC/SiC liners during combustion testing. The purpose of this report is

to document the results of this testing, with an emphasis on the performance of the rich zone combustor liners.

2.0 MATERIAL

Sector components were manufactured by Honeywell Advanced Composites from a SiC/SiC composite developed under the EPM program. A slurry-cast, melt-infiltrated SiC matrix was reinforced with SylramicTM (Dow Corning, Midland, MI) SiC fibers. The fiber tows were woven into 5-harness satin weave cloth. Fiber tow spacings of 18 and 22 ends per inch were utilized to manufacture the parts, resulting in a nominal fiber volume fraction of 35 and 42%, respectively. Four batches of the EPM SiC/SiC material were used to manufacture over 120 parts. More details on the material can be found in reference 9.

3.0 RQL SECTOR RIG CONFIGURATION

3.1 Rig Description

The RQL combustor rig contains two rich zone liner cans transitioning to a 60° sector lean burn zone. The rig was designed by Pratt & Whitney under the HSR program and was installed at NASA Glenn in 1998. Figure 1 is a schematic of the rig, along with images of the individual components. Six different SiC/SiC component geometries were designed and manufactured for the combustor liner. Table 1 contains a list of the number of parts required for a full liner set (ref. 1).

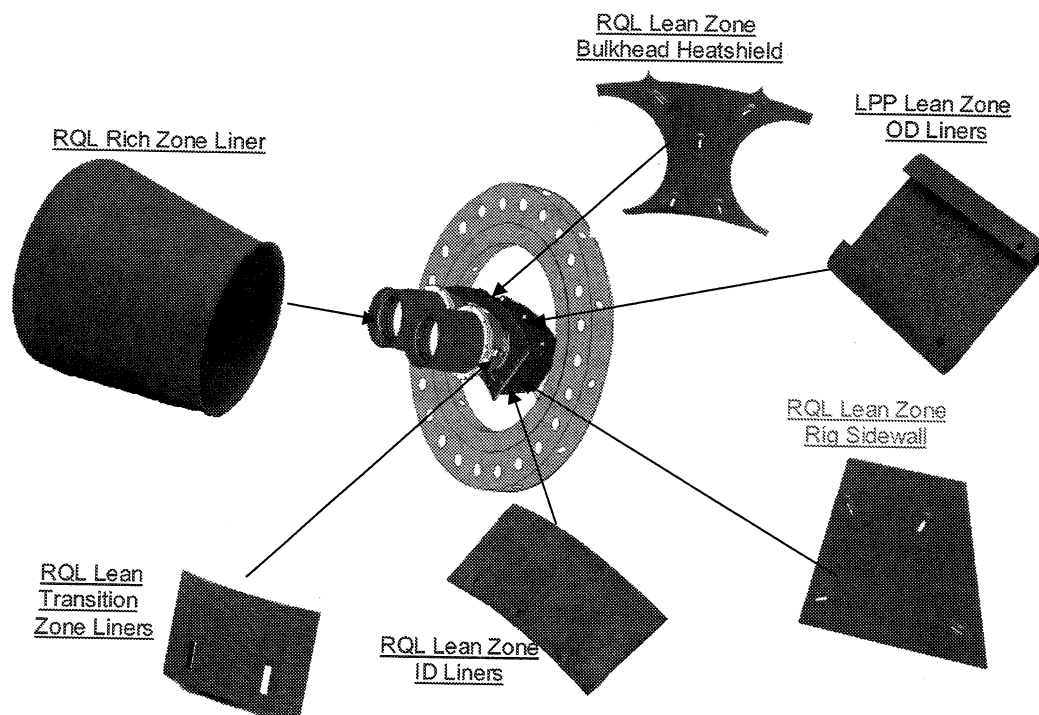


Figure 1 – Schematic of RQL sector rig and images of the SiC/SiC component geometries.

Table 1. – Summary of full SiC/SiC liner set for the sector rig.

Part Name	Abbreviation	Liner Set Requirements
Rich Zone Liner	RZL	2
Lean Transition Liner	LTL	12
Bulkhead Heatshield	BHHS	1 center + 2 halves
Lean Zone Inner Diameter Liner	LZID	6
Lean Zone Outer Diameter Liner	LZOD	3
Lean Zone Sidewall	Sidewall	2
		28

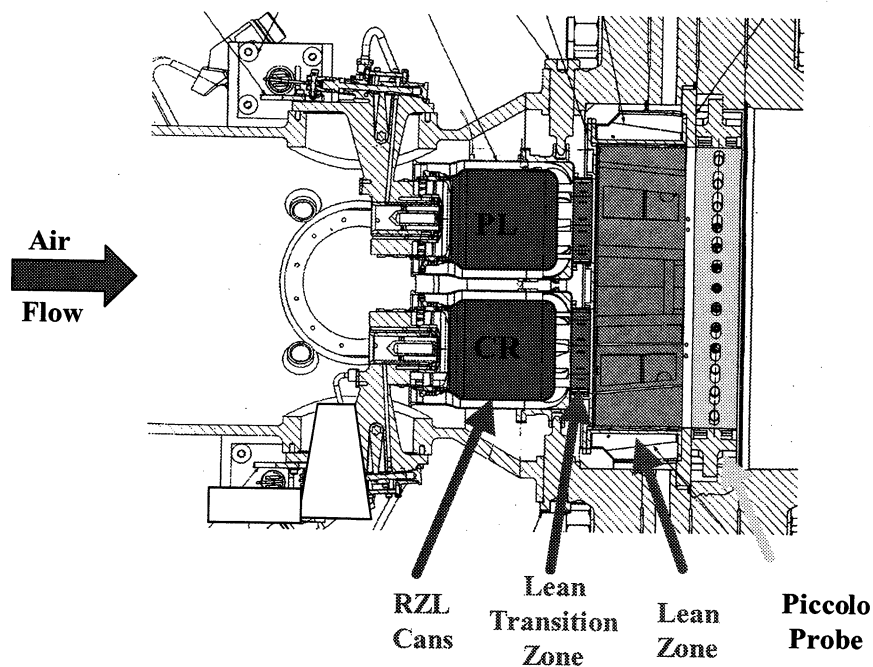


Figure 2 – Top view of the RQL sector rig, showing the main components.

Figure 2 is a schematic of a top view of the RQL sector rig, showing the rig flow path and the main combustor sections. A fuel-rich mixture is ignited by the fuel/air nozzles and enters the rich zone liners. By-pass air is mixed with the burning fuel at the exit of the rich zone liner, resulting in a leaner fuel/air mixture at the entrance of the lean transition zone. Fuel-lean burning is supposed to occur in the lean zone. Gas analysis capability exists in the piccolo probe, which also simulates the presence of the first stage turbine vanes that are normally downstream of the combustor in an aircraft turbine engine.

3.2 SiC/SiC Components

The rich zone liner (RZL) is cylinder with a dome end, about 6 in. long, with an inlet ID of 4.5 in. and exist ID of 3.9 in. The walls of the RZL consists of six SiC/SiC plies, with butt ply slices every 20° around the periphery. Because of the complexity of the geometry, RZLs cannot be manufactured with continuous plies, necessitating the ply splices. The nominal wall thickness is about 0.07 in. A combustor can of similar design was later designed and rig tested by Shi (ref. 7).

The lean transition liners (LTLs) are curved plates, about 1.3 in. wide, covering a 60° arc. Two build-up regions of 12-ply thickness reinforce the locations of the attachment holes, with the other 6 composite plies in the remaining regions. The LTLs are attached to the rig back structure with SiC/SiC Miller attachments (ref. 10).

The lean zone ID liners (LZID) are also curved plates, each covering about a 30° arc of the total 60° sector. A twelve ply thick leading edge reinforces the attachment hole region. The rest of the LZID is six plies thick. These liners are about 2.1 in. wide and are held in place with three superalloy bolts. A full set contains two rows of three liners, the aft liners covering the attachment regions of the upstream liners.

The three lean zone OD liners (LZOD) liners are similar in design to SiC/SiC combustor shrouds tested by Dean, Corman, Luthra, et al. (refs. 3–4). The LZOD's are about 3.9 in. wide and 4.6 in. deep (i.e., in flow direction) and reinforced with 6 composite continuous plies. The LZOD's slide over a mating curved metallic part, which is bolted to the back structure. The two holes in each LZOD are used to mate them to the "ears" on the bulkhead heatshields (Fig. 1).

Three lean zone bulkhead heatshields (BHHS) are required. These liners are attached with Miller fasteners and have 12 ply reinforced attachment regions and nominal 6 ply thickness, similar to LTL's. The left and right BHHSs are 5.1 in. tall and 4 in. wide, and the center BHHS is about 7 in. wide. The circular cut out section ID (4.2 in.) of the BHHSs is sized to the ID of a set of 6 LTL's, as the combustion gas flows from the lean transition section, past the BHHSs and into the lean zone.

The lean zone rig sidewalls are flat panels that are also attached to the back structure with Miller fasteners. This component is an artifact of the rig design, and not representative of a component geometry considered for a combustor liner.

Over 120 components were inspected in the as-manufactured condition. NDE inspections included radiography and C-scans. Microscopic examination, thermal, and mechanical testing were conducted on witness coupons (ref. 1). All this data was used to rank each component or component set, and the best components were selected for initial rig testing.

4.0 INSTRUMENTATION

4.1 Fiber Optic Pyrometry

As part of the sector rig design, Pratt & Whitney supplied a fiber optic pyrometry system to measure the SiC/SiC liner temperatures. Thirty-eight fiber optic sensors and signal conditioners were installed to obtain the temperature of each component type throughout the test cycle. The sensors detected the temperature on the cooled side of the liners.

Testing prior to the current effort degraded these quartz fiber optics, resulting in only two operational channels. A new fiber optic was available and installed to measure the RZL liner temperature. The new fiber optic and an existing operation fiber optic were installed at a location 3.5 in. aft of the fuel/air nozzle for each of the two RZLs.

4.2 Thin Film Thermocouples

Previous experience with the sector rig revealed that the component that is exposed to the highest temperature and has sustained the most damage is the RZL (refs. 1–2). This section is a description of the thin film thermocouples tested on rich zone liners, including installation and configuration.

Two RZLs were each instrumented with two thin thermocouples located 180 degrees apart circumferentially near the trailing edge. The sensors were fabricated in a clean room to minimize possible contamination. A schematic diagram of the layered sensor is shown in Figure 3. The liners were heat-treated at 1200 °C for 50 hours to form a stable, adherent 2–3 μm thick layer of silicon dioxide on the surface. Because of its high resistivity and low reactivity, approximately 6 μm of aluminum oxide was deposited via electron-beam evaporation to form an electrically insulating layer. Type R (Pt/Pt-13Rh) thin film thermocouples were patterned on the alumina with stenciled metal masks. Approximately 5 μm thick films of platinum and platinum-13% rhodium were sputter deposited to form the thermocouple legs. The panels were heat treated at 1000 °C for 5 hours to anneal and stabilize the films. An additional layer of aluminum oxide was sputter-deposited over part of the thermocouples to provide protection from the test environment. However, parts of the thermocouple legs were left exposed to permit leadwire attachment to the films.

Protective Alumina Overcoat
Sensor Elements
E-Beam Deposited Alumina
Thermally grown Silica
SiC/SiC Rich Zone Liner Substrate

Figure 3 – Schematic of the thin film thermocouple layers.

Wires were installed on the cylinders to complete the sensor system. Platinum-13% rhodium and platinum bare leadwires (125 μm diameter) were installed along the length of the cylinders with a bonding process that included applying a SiC-based cement and a plasma-sprayed rokide (alumina-based rod) bond coat and cover coat. This process is designed to protect the leadwires and improve durability. Smaller leadwires (75 μm diameter) were parallel gap welded to the thin films and attached to the bonded 125 μm diameter wires. Figure 4 shows the sensor system on a RZL surface. Sheathed extension cables (1.0 mm diameter) were attached to the 125 μm diameter bare wires and routed out of the test facility.

5.0 TEST FACILITY

The Preheated Combustor and Materials Test Facility (PCMTF) in test cell CE-9 was used to conduct the RQL sector rig testing. The facility (Figure 5) has two flow paths. Side A was configured for the RQL sector rig testing.

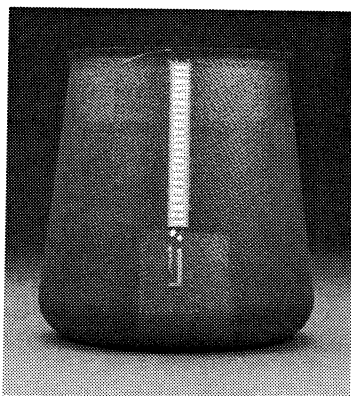
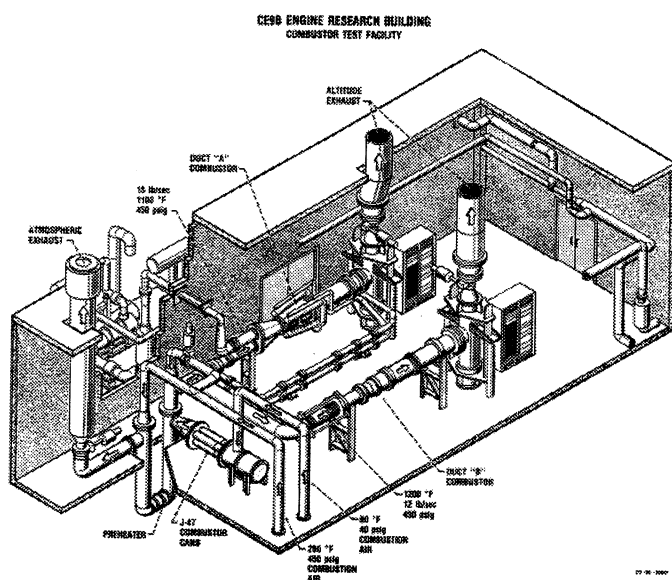


Figure 4 – Photograph of a thin film thermocouple installed on a rich zone liner.



Facility Capabilities:

Max. Flow Rate:
15 lbs/sec.

Max. Inlet Air Temp. (T3):
1100°F

Max. Pressure (P3):
450 psig

Figure 5 – CE-9 Preheated Combustor and Materials Test Facility.

The PCMTF provides 450-psig combustion air for advanced combustor and materials research, at a maximum flow rate of 30 lbs./sec (ref. 11). The nonvitiated combustion air can be heated to temperatures up to 1150 °F by using a natural gas preheater. The preheater consists of four J-47 combustor cans and a counter flow heat exchanger. A liquid jet fuel system exists, with a capability of 11 gallons/minute flow rate at 900 psig. JP5 fuel was burned during the sector rig testing.

The facility has a combustion gas analysis system, which utilized the water-cooled piccolo probe to collect emissions data on Side A. Emission gases that can be analyzed include NO, NO_x, CO, CO₂, H_xC_x, and O₂. From this information, the performance of the combustor can be evaluated.

6.0 TEST CYCLE

The test cycle used during the SiC/SiC sector rig operations is shown schematically in Figure 6. Air temperature (T3), pressure (P3), and flow rate were varied to approximate the anticipated service cycle of the HSCT engine combustor. Actual values of these parameters are omitted from Figure 6 because details of engine operation are proprietary. All aspects of an HSCT flight operation, such as take-off, climb, cruise, and decent, are included in this cycle. Because of PCMTF facility constraints, the order of these operational segments was changed relative to actual operational sequence. When testing continued longer than the 230-minute cycle, the supercruise portion of the cycle was sustained until 40 minutes prior to the end of the testing window. At this point, the sub climb and decent portions of the cycle were completed.

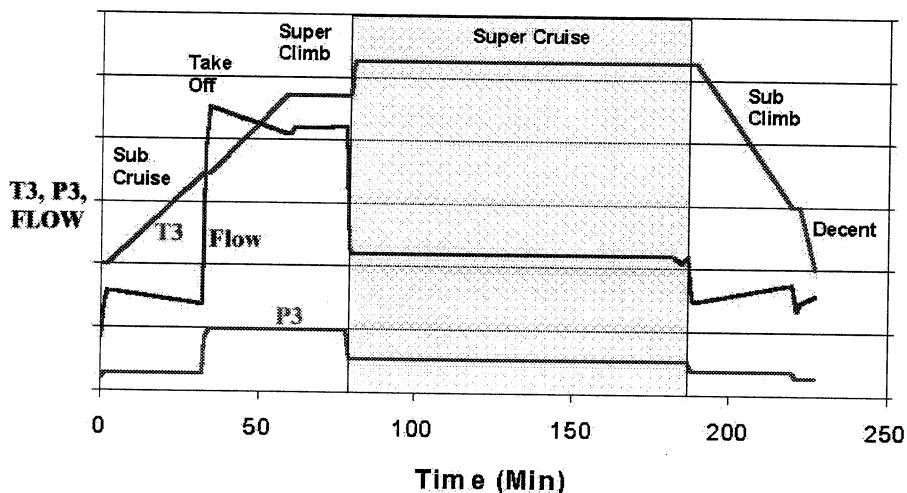


Figure 6 – Cycle used during sector rig testing.

7.0 RESULTS

7.1 Liner Performance

About 56 hours of testing was conducted during 6 days in September and October 2000. Thirty SiC/SiC components were tested, including 26 lean transition zone and lean zone liners that were exposed for the full 56 hours. Two RZLs were tested for 16 hours and were removed when significant damage was detected. The two replacement RZLs were tested for the remaining forty hours, until damage of one of these replacement RZLs resulted in completion of the testing. Details of this damage will be discussed below.

Combined with the 205 hours of testing conducted in 1999, a total of 261 hours of SiC/SiC component testing was completed, as summarized in Table 2. Fifty-four SiC/SiC components were installed and exposed during the combined 261-hour period, including 9 lean zone and 3 lean transition zone liners that were tested for the entire duration. The failure and damage of the RZLs and LTL's that occurred during the previous testing are discussed in ref. 1. The pre-planned post-test characterization of 11 liners that were removed after 115 hours of testing is given in ref. 2.

Table 2 – Summary of Liner Performance during the current study and previous efforts (refs. 1–2)

Total Test Duration (hrs)	Notes on SiC/SiC Liners
14	Failure of two RZLs.
54	Loss of three lean transition liners due to fastener failure.
115	Planned removal of 11 lean transition and lean zone liners for post-test characterization and replacement of RZLs.
205	Removal of two lean transition liners due to a failed fastener and replacement of two RZLs with previously detected cracks. Initiation of the present study.
220	Removal of two RZLs due to detection of cracks.
261	Failure of one RZL and Completion of testing

7.2 Damage of the Rich Zone Liners

Boroscope inspections were performed after every test day and were used to document the condition of all the SiC/SiC liners as well as rig components in the gas path. The only damage that was observed through this method occurred in the rich zone liners. Since two flow paths exist in the sector rig, a convention was adopted to identify the various SiC/SiC liners by labeling them either parking lot (PL) side (i.e., the side of the rig closest to the building parking lot) or control room (CR) side (Table 3).

Table 3 – Rich Zone Liners tested during the current study.

<u>Can ID</u>	<u>Test time, hrs</u>	<u>Rig Side</u>	<u>Installation date</u>	<u>Removal date</u>
555-07-009	15.5	CR	9/1/00	10/3/00
555-07-010	15.5	PL	9/1/00	10/3/00
555-07-005	40.5	CR	10/3/00	10/22/00
253-07-210	40.5	PL	10/3/00	10/22/00

Cracking was found after the first test run of 7.5 hours in the CR side RZL (555-07-009). The crack initiated at the leading edge, grew about 2-3/4 in. along the flow direction, and bifurcated, turning 90° (i.e., in a circumferential direction). Another 90° crack branch existed about 1-3/4 in. from the leading edge (Figure 7). Propagation of these circumferential cracks was observed after the second test run of 8 hours.

After the second test run, cracking that initiated at the leading edge was detected in the PL side RZL (555-07-010) as well. The crack was about 3/4 in. long, in a direction parallel to the flow direction, and it bifurcated. The circumferential portion of this crack spanned over 90° of the RZLs circumference, Figure 8. Relative displacement of the crack faces perpendicular to the flow direction was imaged with the boroscope. To avoid further damage and potential RZL failure during subsequent testing, both RZLs were removed and replaced with new ones. The replacement PL-side RZL (253-07-210) developed a leading edge crack after the third test run. Boroscope inspection after the fourth run imaged a second leading edge crack, 180° apart from the initial crack. The second crack initiated on a fiber cloth splice that was visible on the inner diameter of the RZL (Figure 9). Continued propagation of these two cracks was

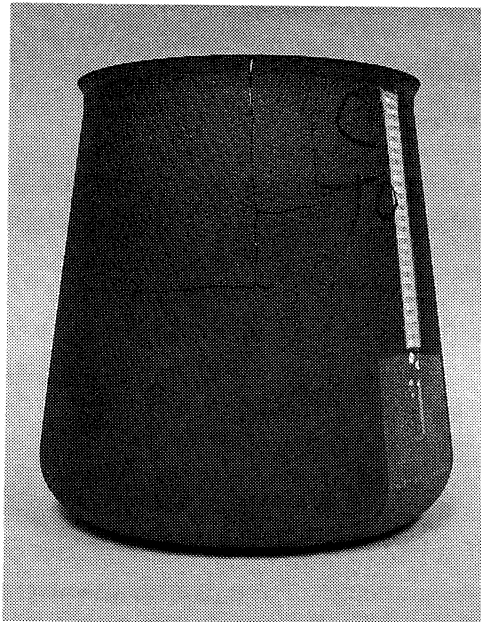


Figure 7 – Post test picture of cracking in rich zone liner 555-07-009.
Note the thin film thermocouple and wire leads.

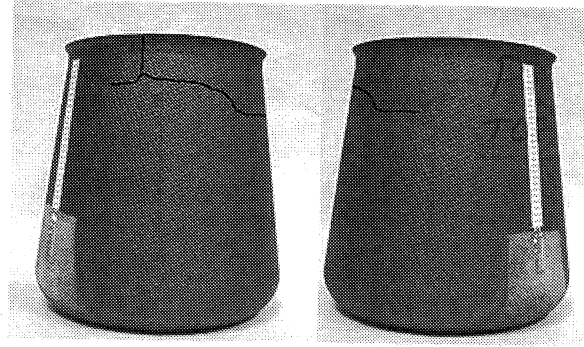


Figure 8 – Post test pictures of rich zone liner 555-07-110, a) initiation site of crack at leading edge and branching in a circumferential direction, b) rotated view the can, showing the location of the crack tip.

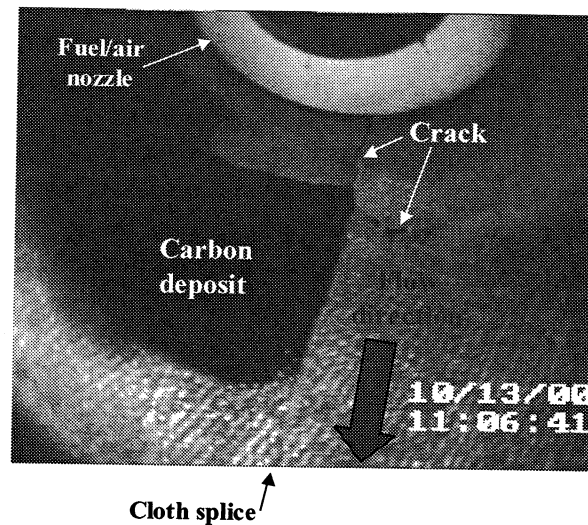


Figure 9 – Boroscope image of the ID of rich zone liner 253-07-210 showing crack initiation and growth from the leading edge on a ply splice.

observed after the fifth run. Both cracks were about 2 in. long, with a 90° branch. These branches were along circumferential directions. Also, a leading edge crack was now visible in the replacement CR-side RZL.

Inspection after the sixth run revealed that failure of the PL-side RZL occurred. An independent 2 in. long by 1-3/4 in. wide section was created when a new leading edge crack linked with an existing crack that had turned in a circumferential direction (Figure 10). Testing was suspended due to this damage. Note that the extensive cracking caused the RZL to split into two halves upon removal from the sector rig.

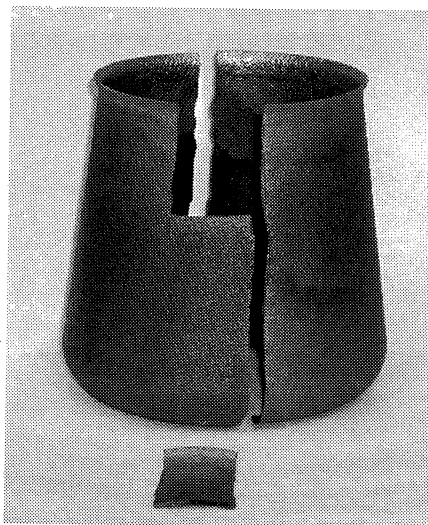


Figure 10 – Post-test view of PL-side RZL (253-07-210) showing damage that occurred after 40.5 hours of testing.



Figure 11 – Post-test image of CR-side RZL (555-07-005). Note the oxidation and crack originating from the leading edge.

A post-test image of the replacement CR-side RZL is shown in Figure 11. Similar to the PL-side RZL, a 2 in. leading edge crack that turned 90° exists.

Carbon deposits are present in every tested RZL (Figure 12). Boroscope inspections revealed that carbon deposits form during the initial test exposure and grow with continued testing. Once formed, these carbon deposits typically remained on the ID of a RZL unless they grow significantly in a direction normal to the flow. In these cases, the forces of the flowing gas stream fracture the carbon deposits. Evidence indicating the results of carbon deposit growth and fracture was the large quantities of carbon nuggets that accumulated in the cooling water used downstream of the combustor.

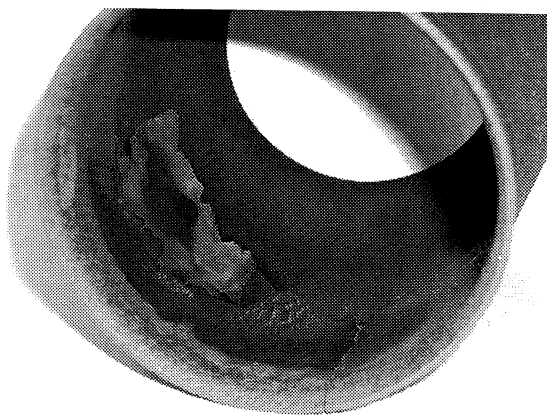


Figure 12 – Carbon deposits and cracking in CR-side RZL (555-07-005) after 40.5 hours of testing.

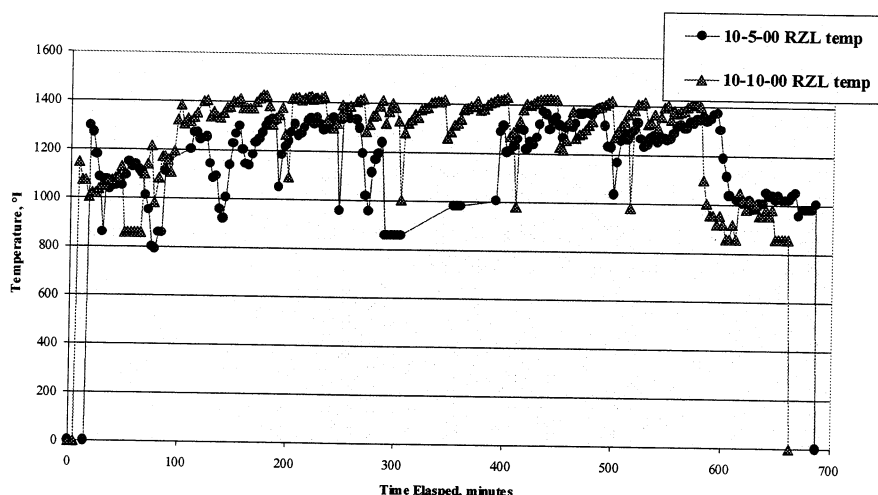


Figure 13 – Rich zone liner temperature measured during sector rig testing.

7.3 Rich Zone Liner Temperature

7.3.1 Fiber Optic Pyrometry Data – Figure 13 shows the temperature of a RZL versus time measured during two of the test runs. The temperature was measured 3.5 in. aft of the fuel/air nozzle and was obtained during the fourth and fifth test runs, when the second set of RZLs was installed. Note that the pyrometry system is not accurate below about 850 °F.

The RZL temperature increases quickly during test initialization, and gradually increases to a maximum range during the supersonic cruise portion of the cycle. However, the temperature never reaches a steady-state value, but cycles up to a maximum. The large temperature spikes that exist occur when the supersonic cruise portion of the cycle is continued beyond its normal

110-minute duration and are therefore an artifact of the test control. The origin of the smaller amplitude temperature cycling is unknown. Also note that during the testing on 10-5-00, a rig operational problem stopped testing during the period of about 280 to 400 minutes.

The average peak temperature measured during the supersonic cruise portion of the cycle is shown in Figure 14. Data obtained during the current study is shown along with some temperature data obtained during the previous 205 hours of testing. The maximum rich zone liner temperatures measured during the current study are within the range obtained during previous sector testing. Figure 14 also shows the axial temperature gradient, which is the difference between the average peak liner temperature and the combustor inlet air temperature, T3. The leading edge of the RZLs is cooled by the inlet air and therefore is at the same temperature. The axial gradients vary from 175 to 515 °F.

7.3.2 Thin Film Thermocouples – The RZLs instrumented with thin film thermocouples were exposed to room temperature air for approximately 220 minutes and heated air for approximately 210 minutes flowing about 2 lbs/s prior to the combustor being lit. This exposure was due to facility problems that prevented the initiation of testing. Only a few temperature data points were recorded during this period, however, the thin film thermocouple data obtained during this time indicated that the material surface temperature was between the combustor inlet and combustor exit temperatures. Once the combustor was lit, the thin film thermocouple output was erratic as the temperatures were increasing. The output of two thin film thermocouples and the combustor inlet and exit temperature data are shown in Figure 15. The thermocouple data eroded with time after exposure to the elevated temperatures.

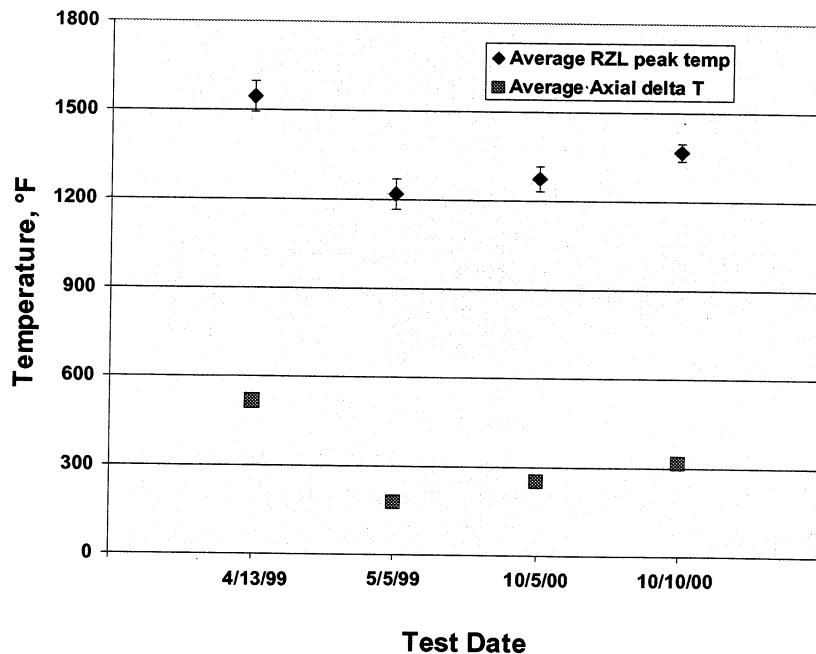


Figure 14 – Average peak temperature of rich zone liners measured during the supersonic cruise portion of the test cycle and calculated axial delta T as a function of test date.

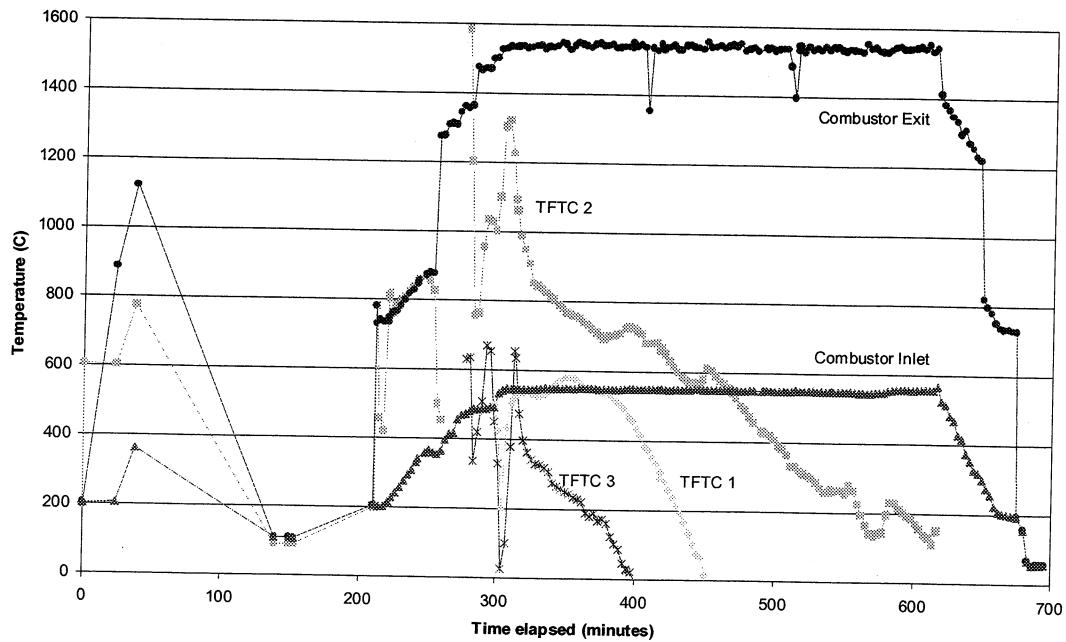


Figure 15 – Thin film thermocouple data obtained during sector rig testing.



Figure 16 – Condition of a thin film thermocouple on a rich zone liner after combustion exposure.

Post-test analysis of the thermocouples revealed that the thin film thermocouples were intact and electrically continuous. There appeared to be very little physical damage to the films (Figure 16). However, the welds that held the platinum-13% rhodium wires to the films failed. The aluminum oxide insulation films were intact for all but one of the thermocouples. The fourth thermocouple had some flaking in the aluminum oxide film, resulting in lowered

electrical resistance in the film. Despite cracking in the rich zone liners, the leadwires that extended the length of the hardware were still intact and continuous. Because the wires that extended beyond the edge of the RZLs were damaged during removal from the test rig, these wires could not be evaluated.

8.0 DISCUSSION

8.1 Rich Zone Liner Damage

The cracking of the RZLs that occurred is similar to that observed in others tested in 1999 (ref. 1). Three factors may have contributed to the damage observed in the RZLs tested during the present study, namely; material quality, thermal gradients, and mechanical loads due to attachment of the liners to the rig.

As part of the characterization of the as-manufactured RZLs, the hoop tensile properties were measured. A hydrostatic ring test facility was used to test two witness coupons from each component at room temperature (ref. 11). The strength, modulus, and strain to failure for the four rich zone liners are compared to data obtained from plate specimens machined from the same vintage material in Figure 17. On average, the rich zone liner witness coupons had 45% lower strength, 70% lower failure strain, and 20% higher modulus than the plate specimens. Thus, the properties indicate that the rich zone liner composite was more brittle and weaker than material in plate form. Note that panel data was the basis for the component design.

Quality of material may have contributed to the severity of damage observed. The as-manufactured components were ranked based on NDE results, mechanical and thermal properties from witness coupons, and microstructural quality. The highest rated rich zone liners were selected for initial rig testing. Three sets of RZLs (six total) were tested during the first 205 hours of sector rig operation in 1999. The first set failed catastrophically due to design issues with the attachment system. The other two sets of RZLs tested in 1999 did develop cracks, but had less damage (in terms of total crack length) and were tested longer (65 and 80 hrs) than those tested in this study. The four RZLs discussed in this paper were

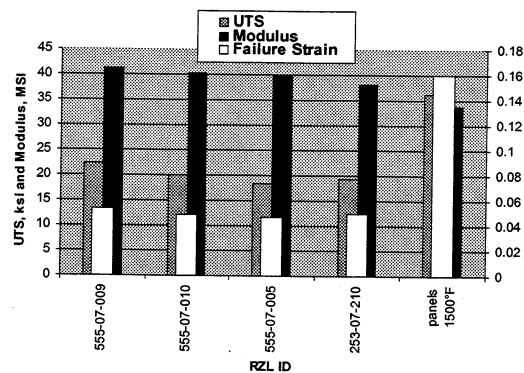


Figure 17 – As- manufactured strength, modulus, and failure strain obtained through ring burst tests for the rich zone liners exposed in the sector rig.

ranked lower than the six tested in 1999. In particular, the last PL-side RZL (253-07-210) that failed (Figure 10) had the lowest rank of the ten.

The most critical aspect of material performance under the combustion environment is managing the thermal stresses (refs. 8–9). Liner temperature measurements indicated that a thermal gradient exists along the flow direction during operation (Figure 14). The gradient is based on temperatures measured along one linear section of the RZLs. It is likely that temperatures varied around the circumference of the liners, as a variation in oxide color (and therefore oxide thickness) was generally observed in tested RZLs (Figure 11). The presence of carbon deposits on the ID (Figure 12) likely affected the liner temperatures. Also, the thermal stresses, that are most important to design of the liners, are due to through-thickness temperature gradients. Thus, it is possible that the data in Figure 14 represents a lower bound for temperature gradients that would be critical to liner durability.

As part of this study, modifications of the fuel/air nozzles were made in an attempt to reduce the flow of by-pass air into the combustion stream and thus reduce the axial thermal gradient in the RZLs. The fuel/air nozzles contain seals that were designed to minimize the by-pass air flowing into the combustor. The presence of by-pass air in the combustion flow cools the upstream portion of the RZLs, but does not affect the temperature in the hottest portion of the liner, the aft end. This was verified with pyrometry data from tests conducted in 1999. The axial temperature gradients measured during tests conducted in 1999 bounds the gradients measured during the present study (Figure 14). Thus, the modifications of the fuel/air nozzles did not reduce the thermal gradients along the flow direction.

Two rich zone liners failed during initial testing of the sector rig. A significant force interaction occurred between the rich zone liners and the spring holding them in place at the leading edge, resulting in the failure (ref. 1). After the spring was redesigned to be more compliant, catastrophic failure did not reoccur. In the present study, crack initiation at the leading edge was observed for all RZLs. It appears that the modified spring attachment method needs additional alteration to reduce the axial and hoop loading on the cans and thus eliminate cracking.

8.2 Thin Film thermocouples

The post-test analysis of the sensors indicated that the thin films and leadwires survived the test conditions, however the welds between the wires and thin films did not. The wires did not maintain full and intimate contact with the films. This may have contributed to the erratic data that occurred during the temperature increase after the combustor was lit. In particular, the platinum-13% rhodium wires failed to remain in contact with the films. This may have been due to oxidation of the rhodium in both the wire and the exposed film. During sensor fabrication, the film was not completely covered by the protective aluminum oxide overcoat to allow attachment of the leadwires. The degradation in the output signals during high temperature exposure may have been caused by a change in the composition of the exposed films and fine wires. Analysis of the thermocouple data indicates that the connections between the wires and films failed prior to the initiation of the actual sector testing, during the initial period during which the hardware was exposed to high temperature, high flow air. The

thin film thermocouples were installed in a region of the rig that was exposed to the cooling air flow. It is also possible that the force of this air flow damaged the welds between the wires and the thin films.

Assuming that all of the thermocouples changed composition at the same rate, the data indicates that there is a variation in temperature across the surface of the RZLs. The temperature prior to the signal degradation indicates that the temperature delta around the periphery was as high as 500 °C.

While the thin films proved to be physically durable during this testing, the failure of the wires and the degradation in the signal output demonstrates that the thin film-to-leadwire connections need to be improved for durability and the thin films need to be more fully protected from the harsh test environment.

9.0 SUMMARY

1. Fifty-six hours of testing of SiC/SiC combustor liners was conducted using the RQL sector rig. Combined with the previous efforts, a total of 260 hours of testing was conducted on fifty-four components. Twelve of the fifty-four components were tested for the entire 260-hours. This unique capability for testing ceramic matrix composites in this aeronautic gas turbine engine combustion environment provided data unavailable from any other facility.
2. Damage, in the form of cracks, was observed in one of the component types, the rich zone liners. In all four rich zone liners tested, cracks initiated at the leading edge, grew along the flow direction, and bifurcated, turning 90° in a circumferential direction. The cracking is similar to that observed in rich zone liners tested in 1999. Three factors may have contributed to this damage, namely: material quality, thermal gradients, and mechanical loads due to attachment of the liners to the rig.
3. The capabilities of GRC-developed thin film thermocouples for measurement of CMC liner temperatures were evaluated. Thin film thermocouple data was obtained during the first 2 hours of sector rig operation, after which the output was erratic. The thin film sensors and leadwires survived the test conditions, however the welds between the wires and thin films did not.

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